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Patentanmeldung Nr. Patent application No. Demande de brevet n°

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If no title is shown please refer to the description.
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Lithium niobate optical modulator

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LITHIUM NIOBATE OPTICAL MODULATOR

This invention relates to lithium niobate optical modulators. In particular, the invention relates to lithium niobate optical modulators with electrode structures enabling operation at high frequencies of up to 40GHz.

As the demand for telecommunications services and bandwidth has boomed, the need for, and advantages of, external modulation in fibre-optic transmission systems has been firmly established. Lithium niobate is today one of the most important dielectric materials in the field of integrated optics, both for research and for technological applications. This importance is due to the strong correlation between the optical properties of the crystal, its refractive index, and the application of various kinds of external fields; namely electric fields (electro-optic effect), sound waves (acousto-optic effect) and electromagnetic waves. Lithium niobate external modulators provide both the required bandwidth and a means for minimizing the effects of dispersion that limit system performance.

Almost all lithium niobate optical modulators are traveling wave devices, in which the optical waveguide comprises a Mach-Zehnder interferometer (MZI). High speed, broad bandwidth optical modulators are made by constructing a particular electrode structure on the buffer layer of the MZI modulator, which prevents light propagating through the waveguide path from being absorbed by the electrode metal. MZI modulators operate with a push-pull electrode structure, so that fields of opposite polarity operate on each arm of the waveguide. These fields serve to change the index of the electro-optic lithium niobate, which in turn alters the phase of the light traveling in each waveguide, and thus allows operation of the interferometer. The optical phase or amplitude modulation results from an interaction between the optical wave in the optical waveguide and the microwave wave guided by the electrode structure.

Lithium niobate MZI devices have the potential for very broadband operation, but they are limited by, inter alia, mismatches between optical and microwave effective refractive indices (and hence mismatches between the velocities of the electrical and optical signals), electrode electrical losses, electrode impedance and drive voltage. Specifically, a velocity mismatch between the velocities of the electrical and optical signals together with electrical losses strongly curb modulator electro-optical response; high electrode impedance is needed to prevent reflections when the modulator is connected to a signal electrical driver; and low driving voltages are a prerequisite. Introducing a very thin dielectric layer

between the MZI structure and the electrodes can provide velocity matching between the electrical and optical fields, low electrical losses and high impedances, but requires higher driving voltages. Modulators made accordingly based on both X-cut and Z-cut lithium niobate substrates perform well up to 10GHz. For operation at frequencies in excess of 10GHz using the same driving voltage and microwave refractive index values, Z-cut lithium niobate substrates enable lower electrical losses and higher impedances.

Typical electrode structures used for lithium niobate MZI modulators include coplanar strip structures, as shown in fig. 1, having respective electrodes 1, 3 disposed on the buffer layer 5 directly above each of two parallel waveguides 7, 9 forming the MZI. Such structures provide high impedance, but also high electrical losses. Asymmetric coplanar strip electrode structures, as shown in fig. 2, are similar to the coplanar strip structures of fig. 1 except that the ground electrode 3 is much wider than the hot electrode 1. These structures present problems with electrical-optical signal velocity matching, which may be overcome by use of very thick gold electrodes (>30μm), though such thicknesses are difficult to obtain using standard processes. Such structures also cannot achieve very low electrical losses suitable for high frequency applications, and their structure does not permit easy electrical connections to be made within a package. Coplanar waveguide structures, as shown in fig. 3, are similar to the asymmetric coplanar strip structures of fig. 2 with a second wide ground electrode 4 spaced symmetrically on the other side of the narrow hot electrode 1. These structures can provide good electrical loss characteristics, but to achieve optical-microwave effective refractive index matching and high impedance requires an increase in buffer layer thickness which then requires higher driving voltages. One way to achieve optical-microwave effective refractive index matching and high impedance using a thinner buffer layer is to use narrow ground electrodes. However, narrow electrodes suffer from very high electrical losses.

There remains a need for a lithium niobate optical modulator design which is capable of operating at frequencies in excess of 10GHz with matching optical and microwave effective refractive indices, low drive voltage and electrode electrical losses, and high electrode impedance.

According to the invention, there is provided an optical modulator comprising a Z-cut lithium niobate substrate on which is formed a Mach-Zehnder interferometer having two generally parallel waveguides lying beneath a buffer layer of dielectric material. First and second ground electrodes and a hot electrode are disposed on the buffer layer, the first and

second ground electrodes being spaced either side of the hot electrode, the hot electrode and the first ground electrode being proximate to at least a part of the respective waveguides. The hot electrode and the first ground electrode have a width not exceeding 15μm and the spacing between the first ground and hot electrodes is smaller than the spacing between the second ground and hot electrodes.

By use of a ground electrode with a width not exceeding 15μm, the inventors have been able to obtain a good match between the microwave and optical effective refractive indices, even while providing a wider spacing between the second ground and hot electrodes than that between the first ground and hot electrodes, so maintaining low electrical losses and good impedance characteristics. This action does not affect the driving voltage since neither the buffer layer thickness nor the spacing between the first ground and hot electrodes are adversely changed. Futhermore, by appropriate selection of geometrical parameters, it is possible to provide a modulator structure with a very low residual chirp value.

Preferably, the spacing between the first ground and hot electrodes is between 10 and 30μm and the spacing between the second ground and hot electrodes is larger, between 20 and 80μm.

Suitably, the width of the hot electrode and the first ground electrode is between 5 and 15μm, and preferably substantially the same as the width of the waveguides.

According to a preferred embodiment, the second ground electrode is at least ten times wider than the hot electrode and the first ground electrode. Use of the (second) wide ground electrode ensures low electrical loss, while the combination with the (first) narrow ground electrode ensures low driving voltage and high impedance. The narrow ground electrode further serves to reduce the microwave effective refractive index relative to the optical refractive index.

Preferably, the dielectric material comprises silicon dioxide with a thickness between 0.4 and 1.5μm, and the electrodes comprise gold having a thickness between 15 and 50μm.

Additional features and advantages of the invention will be set forth in the detailed description which follows, and in part will be readily apparent to those skilled in the art from the description or recognized by practicing the invention as described in the written description and claims hereof, as well as the appended drawings. It is to be understood that both the foregoing description and the following detailed description are merely exemplary

of the invention, and are intended to provide an overview or framework to understanding the nature and character of the invention as it is claimed.

The accompanying drawings are included to provide a further understanding of the invention, and are incorporated in and constitute a part of this specification. The drawings illustrate one or more embodiments of the invention, and together with the description serve to explain the principles and operation of the invention.

Figs. 1 to 3 are sections through respective conventional coplanar strip, asymmetric coplanar strip and coplanar waveguide Z-cut modulator structures;

Fig. 4 is a section through a conventional X-cut modulator structure;

Fig. 5 and 6 are section and plan views of a preferred modulator structure according to the invention;

Figs. 7 and 8 are section and plan views of a second modulator structure according to the invention;

Figs. 9 to 12 are graphs showing the dependence of drive voltage, electrical loss, microwave index and impedance against ground electrode widths; and

Fig. 13 is a graph showing the dependence of residual chirp on electrode spacing in the modulator of Figs. 5 and 6.

A preferred asymmetric coplanar waveguide modulator structure according to the invention, shown in Figs. 5 and 6, comprises a Z-cut lithium niobate substrate 21 with a thickness of around 500μm presenting an optical MZI on its surface. The MZI comprises a mid section having two generally parallel waveguides 23, 25 which converge at either end into single input and output waveguides 22, 26. The parallel waveguides are formed in the plane of the surface of the substrate by a standard titanium diffusion process well known to those skilled in the art of modulator design. The parallel waveguides 23, 25 are 20μm apart with a depth of around 6μm and a width of around 10μm. A buffer layer 27 of silicon dioxide having a dielectric constant of around 4 and a thickness of 1.0μm is grown by means of a conventional electron beam evaporation process directly on the surface of the lithium nioboate substrate in which the waveguides 23, 25 are formed. Three parallel gold electrodes 29, 31, 33 are grown on the buffer layer 27 to a thickness of 20μm. Two of the electrodes 29, 31 are disposed directly above the parallel waveguides 23, 25 with a width of around 10μm and a length extending to just short of the ends of the parallel sections of the waveguides 23, 25. The third electrode 33 is spaced 30μm from the middle electrode 31 with a width of 150μm and the same length as the other electrodes.

Using the middle electrode 31 as the hot electrode, the narrow electrode 29 to the side of the hot electrode as a first ground electrode and the wide electrode 33 on the other side of the hot electrode 31 as a second ground electrode, the asymmetric coplanar waveguide modulator structure described functions well at frequencies up to and including 40GHz. The narrow first ground electrode 29 ensures that driving voltages may be kept low while maintaining a high impedance. Fig. 9 shows the effect of increasing ground electrode widths on drive voltage, and fig. 12 shows the effect of increasing ground electrode widths on impedance. The narrow first ground electrode 29 also serves to reduce the microwave effective refractive index, enabling it to be brought down to match the optical refractive index, while still widening the space G2 between the second ground electrode 33 and the hot electrode 31 to benefit from low electrical loss and high impedance. Thus, the buffer layer may be kept within parameters for maintaining low driving voltages. The effect of increasing ground electrode widths on the velocity matching parameter is demonstrated graphically in fig. 11. The wide second ground electrode 33 on the other hand ensures low electrical loss, as demonstrated in fig. 10.

Table 1 provides a comparison between critical geometrical and performance parameters of the asymmetric coplanar waveguide modulator structure as shown in figs. 5 and 6 (invention) and two coplanar waveguide modulator structures as shown in fig. 3, one with wide ground electrodes (CPW "inf") and one with narrow ground electrodes (CPW "fin"):

Table 1

Parameter	W (μm)	G1 (μm)	G2 (μm)	FW1 (μm)	FW2 (μm)
Invention	7	18	25	7	Inf
CPW "inf"	7	18	18	Inf	Inf
CPW "fin"	7	18	18	7	7

Parameter	t (μm)	τ (μm)	N_m	Z_0 (Ω)	α (dB/cm)	$V_\pi \cdot L$ (V·cm)
Invention	27	0.65	2.14	44	2.5	11
CPW "inf"	27	0.65	2.21	34	2.5	11
CPW "fin"	27	0.65	2.11	41	3	10.7

where the geometrical parameters are as shown in fig. 5, N_m is the microwave effective refractive index, Z_0 is the impedance, α is the electrical loss figure, and $V_\pi L$ is the drive voltage.

As can be seen, CPW "inf" gives a high microwave effective refractive index figure (2.21), while CPW "fin" has large electrical losses (3dB/cm). However, the structure

according to the invention displays the advantageous electrical loss figure of CPW "inf" and the velocity matching characteristics of CPW "fin" with high impedance and the same drive voltage.

In external modulators, frequency chirp arises from phase modulation superposed on the modulated optical signal due to unequal modulation applied to the respective arms of the interferometer. If the integral of the corresponding electrical and optical fields for the two arms are not equal, a residual chirp arises. For X-cut modulators, an example of which is shown in fig. 4, the electrode structure is generally symmetrical with the optical waveguides 7, 9 being positioned beneath the buffer layer 5 but symmetrically between the electrodes 1, 3, 4, so the relative driving voltages are the same. Provided there are no spurious effects, then no residual chirp is expected.

For Z-cut modulator structures such as that shown in fig. 3, the electrical and optical structure cross sections are asymmetric, with the optical waveguides being placed beneath the hot electrode and one of the ground electrodes. Typical expected driving voltages for such a structure would be 10-15Vcm and 70-100Vcm for the respective arms, with the integral of the fields relating to the hot electrode arm being much higher than that relating to the other arm, leading to a fixed residual chirp. However, with the structure of the embodiment shown in figs. 5 and 6, the narrow ground electrode 29 over the waveguide 23 gives rise to driving voltages much closer to those exhibited by the coplanar strip structure of fig. 1, typically of the order of 15-25Vcm for the hot electrode arm and 20-30Vcm for the ground electrode arm. Such close driving voltages lead to lower residual chirp than could be expected from the coplanar waveguide and asymmetric coplanar waveguide structures of figs. 3 and 2 respectively. Fig. 13 shows the effect that varying the spaces G1 and G2 between the hot electrode and the two ground electrodes in the structure of figs. 5 and 6 can have on residual chirp. For a fixed space G1, increasing G2 has the general effect of decreasing residual chirp. Conversely, for a fixed space G2, increasing G1 has the general effect of increasing residual chirp. In particular, by properly managing the geometrical parameters of the structure in fig. 5, residual chirp values lower than 0.1 (usually considered to be a zero-chirp modulator) can be achieved.

In order to benefit from the respective advantages of the narrow and wide ground electrodes as described above requires that the wide electrode be at least ten times wider than the narrow electrode, and the narrow ground electrode to be preferably the same width as the hot electrode.

Figs. 7 and 8 show an alternative asymmetric coplanar waveguide structure according to the invention in which the second ground electrode is the same width as the other two electrodes. This structure achieves low driving voltages and high impedance, but it does suffer from higher electrical loss than the structure of figs. 5 and 6.

It will be apparent to those skilled in the art that various modifications and variations can be made to the present invention without departing from the spirit or scope of the invention. Thus, it is intended that the present invention cover the modifications and variations of this invention provided they come within the scope of the appended claims and their equivalents.

Any discussion of the background to the invention herein is included to explain the context of the invention. Where any document or information is referred to as "known", it is admitted only that it was known to at least one member of the public somewhere prior to the date of this application. Unless the content of the reference otherwise clearly indicates, no admission is made that such knowledge was available to the public or to experts in the art to which the invention relates in any particular country (whether a member-state of the PCT or not), nor that it was known or disclosed before the invention was made or prior to any claimed date. Further, no admission is made that any document or information forms part of the common general knowledge of the art either on a world-wide basis or in any country and it is not believed that any of it does so.

Claims

1. Optical modulator comprising a Z-cut lithium niobate substrate on which is formed a Mach-Zehnder interferometer having two generally parallel waveguides lying beneath a buffer layer of dielectric material, and first and second ground electrodes and a hot electrode disposed on the buffer layer, the first and second ground electrodes being spaced either side of the hot electrode, the hot electrode and the first ground electrode being proximate to at least a part of the respective waveguides, characterised in that the hot electrode and the first ground electrode have a width not exceeding 15μm and the spacing between the first ground and hot electrodes is smaller than the spacing between the second ground and hot electrodes.

2. Optical modulator according to claim 1, wherein the spacing between the first ground and hot electrodes is between 10 and 30μm and the spacing between the second ground and hot electrodes is between 20 and 80μm.

3. Optical modulator according to claim 1 or 2, wherein the width of the hot electrode and the first ground electrode is between 5 and 15μm.

4. Optical modulator according to claim 3, wherein the width of the hot electrode and the at least one ground electrode is substantially the same as the width of the waveguides.

5. Optical modulator according to any preceding claim, wherein the second ground electrode is wider than the hot electrode and the first ground electrode.

6. Optical modulator according to claim 5, wherein the second ground electrode is at least ten times wider than the hot electrode and the first ground electrode.

7. Optical modulator according to any preceding claim, wherein the dielectric material comprises silicon dioxide with a thickness between 0.4 and 1.5μm.

8. Optical modulator according to any preceding claim, wherein the electrodes comprise gold having a thickness between 15 and 50μm.

Abstract

LITHIUM NIOBATE OPTICAL MODULATOR

An optical modulator is provided which is capable of operating at frequencies in excess of 10GHz. The optical modulator comprises a Z-cut lithium niobate substrate (21) on which is formed a Mach-Zehnder interferometer having two generally parallel waveguides (23, 25) lying beneath a buffer layer of dielectric material (27). First and second ground electrodes (29, 33) and a hot electrode (31) are disposed on the buffer layer (27), the first and second ground electrodes (29, 33) being spaced either side of the hot electrode (31), the hot electrode (31) and the first ground electrode (29) being proximate to at least a part of the respective waveguides (25, 23). The hot electrode (31) and the first ground electrode (29) have a width not exceeding 15μm and the spacing (G1) between the first ground and hot electrodes (29, 31) is smaller than the spacing (G2) between the second ground and hot electrodes (33, 31).

Fig. 5

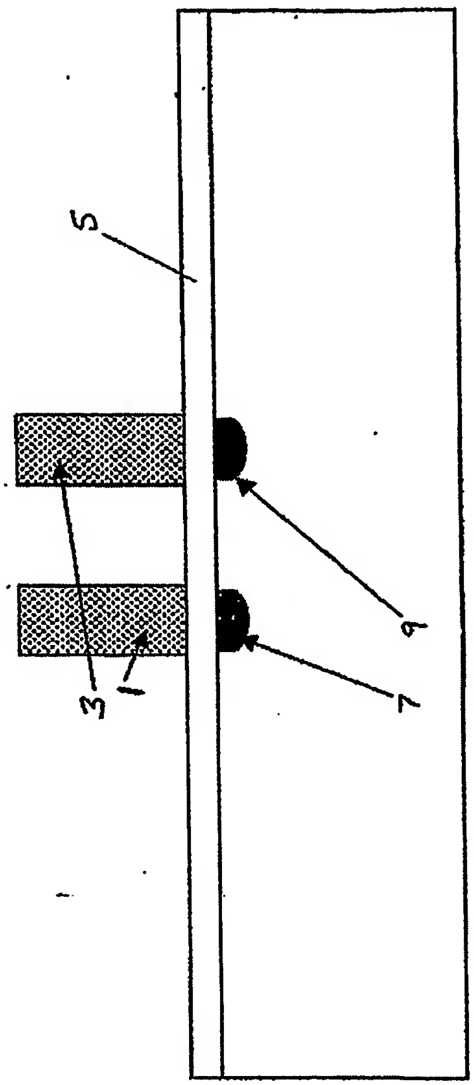


Fig. 1

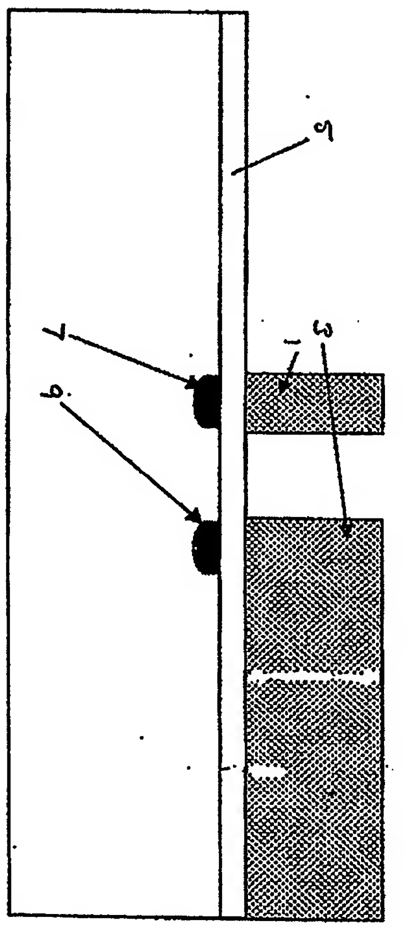


Fig. 2

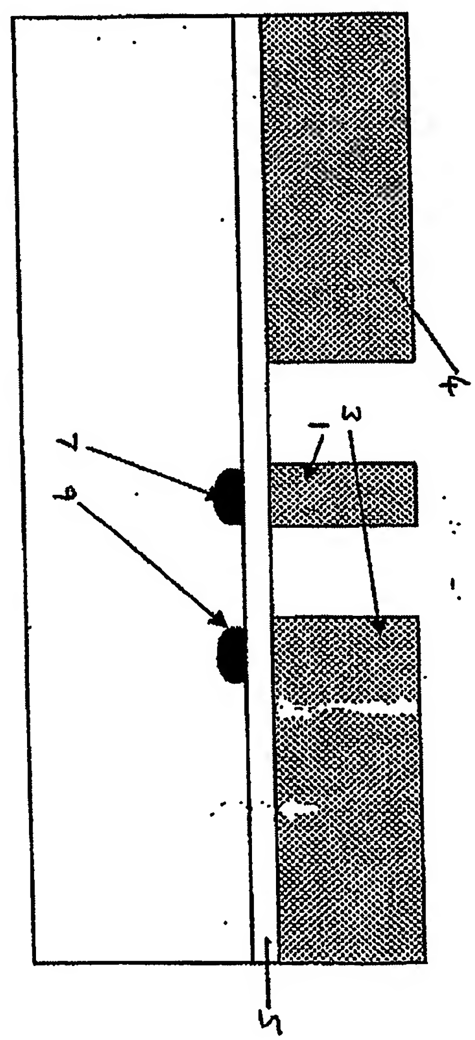
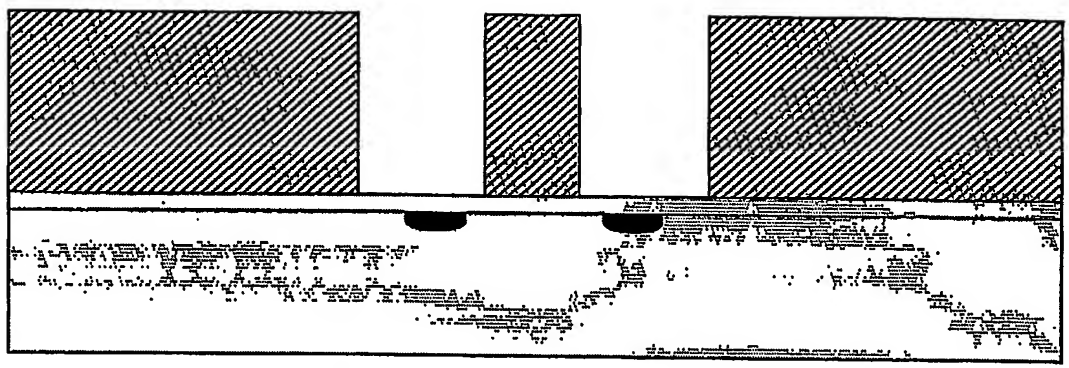


Fig.3

FIG. 4

5



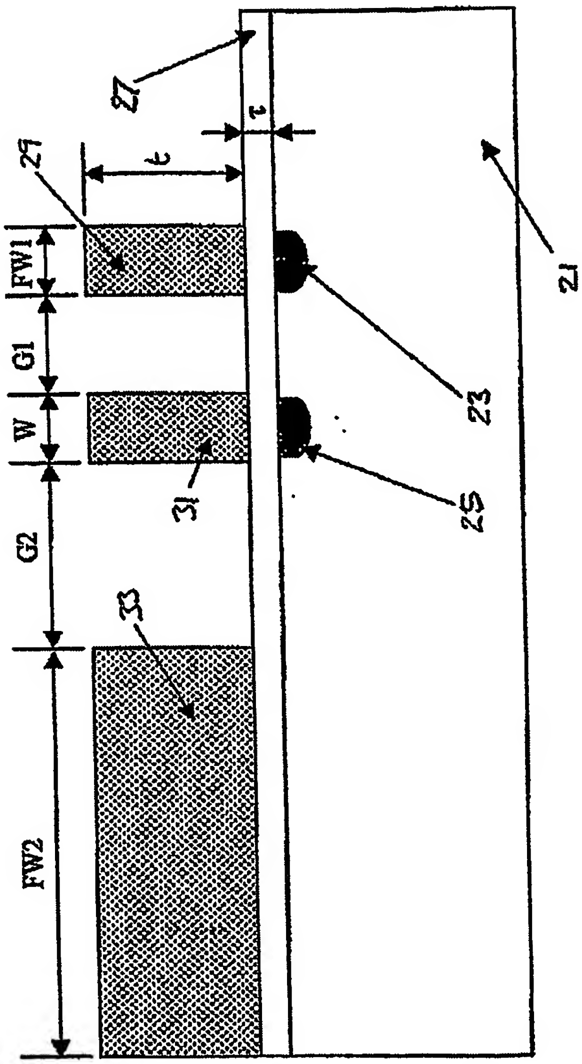


Fig 5

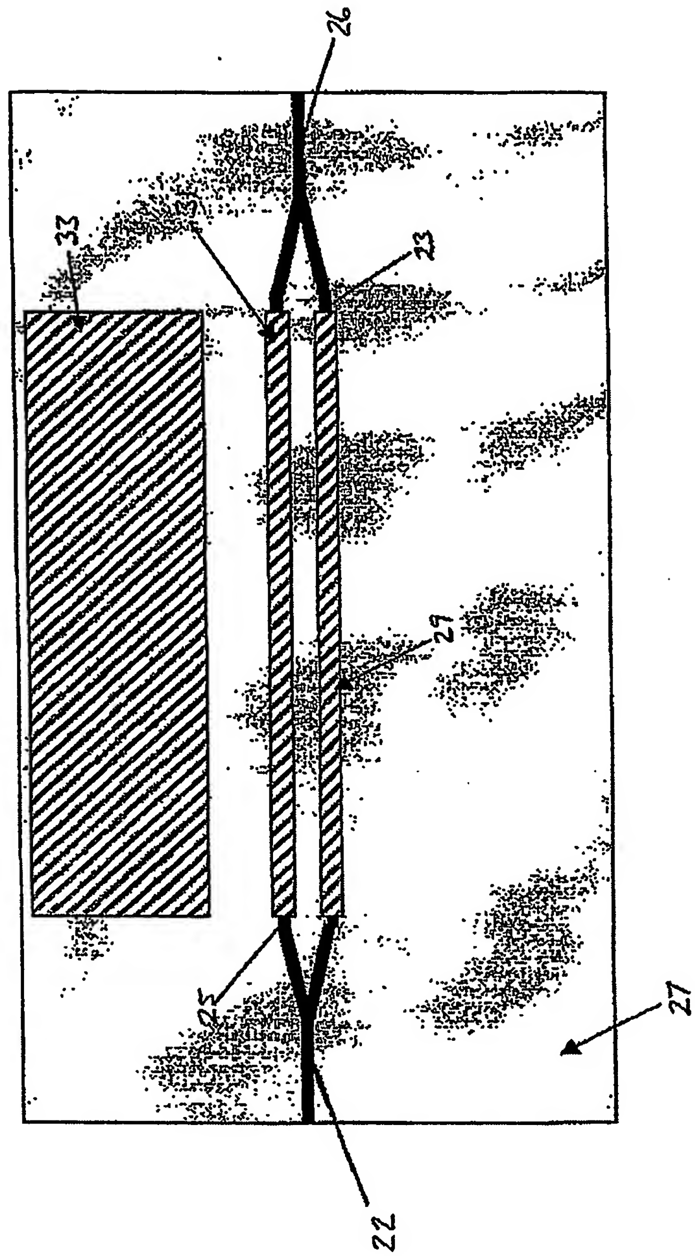


Fig. 6

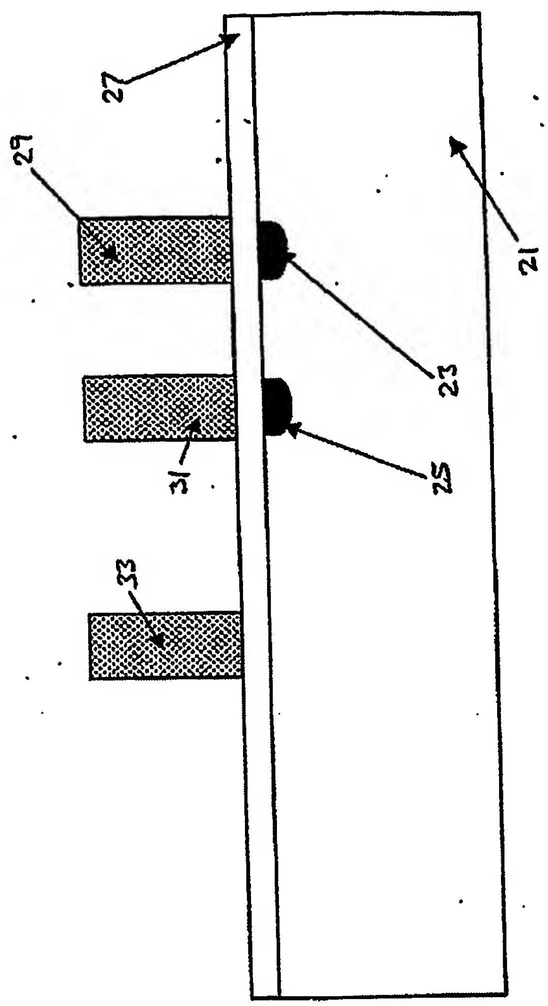


Fig. 7

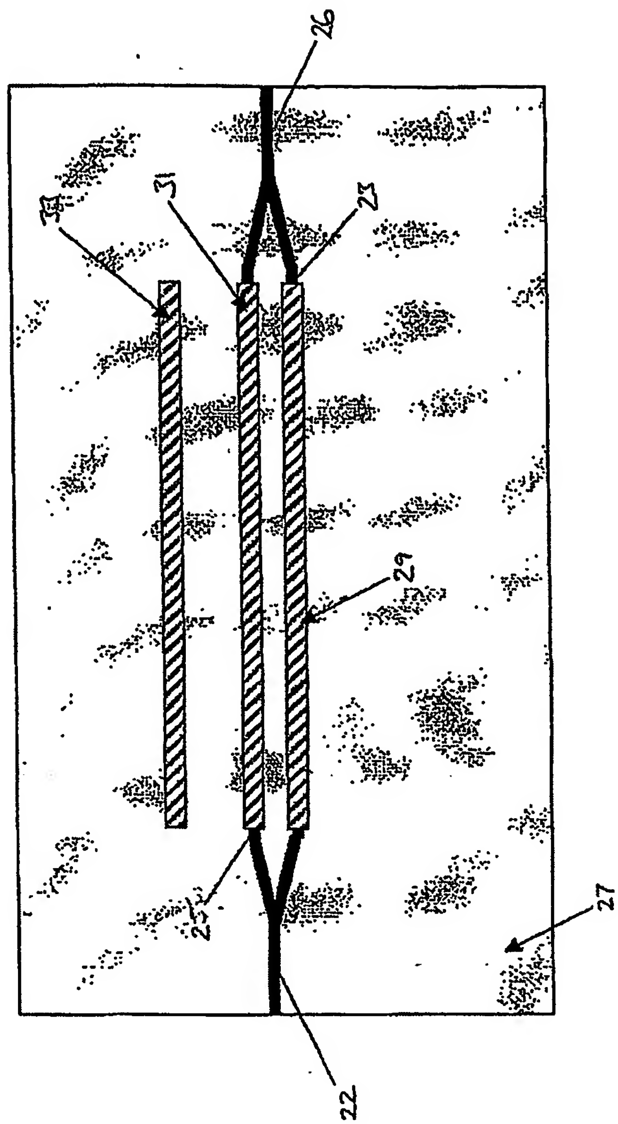
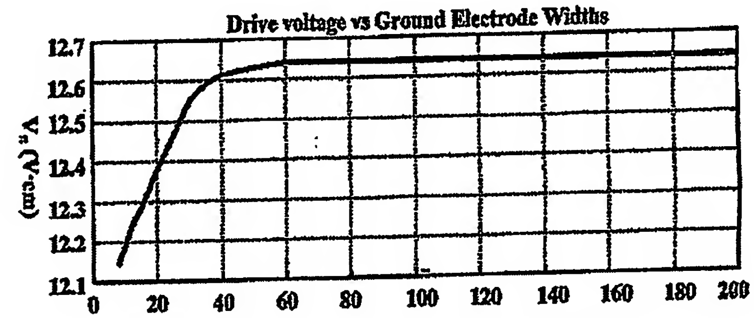


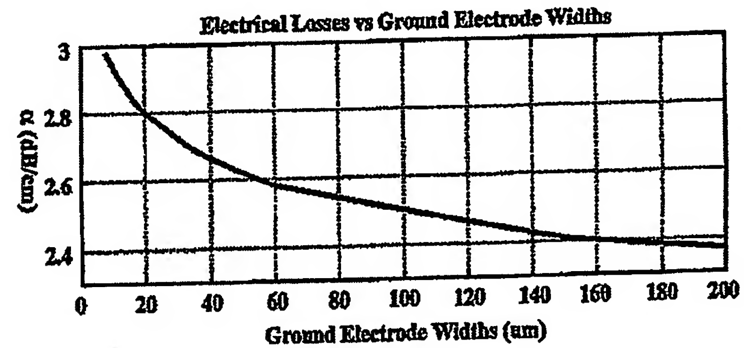
Fig. 8

Fig 9



Drive voltage vs Ground Electrode Widths
V_π (V·cm)
12.7
12.6
12.5
12.4
12.3
12.2
12.1
0
20
40
60
80
100
120
140
160
180
200

Fig 10



Electrical Losses vs Ground Electrode Widths
α (dB/cm)
3
2.8
2.6
2.4
0
20
40
60
80
100
120
140
160
180
200
Ground Electrode Widths (um)

Fig. 11

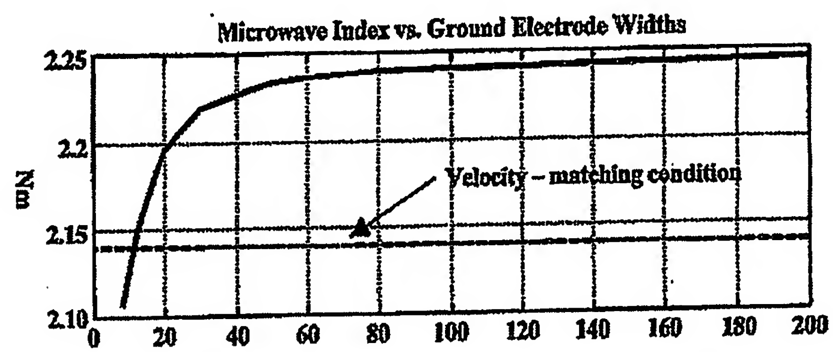
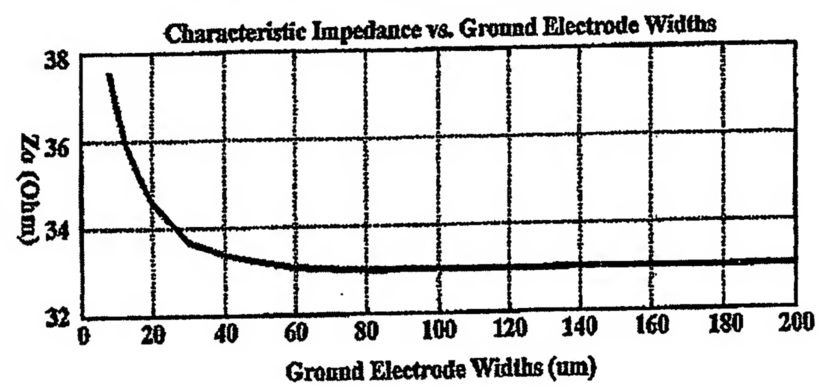

Microwave Index vs. Ground Electrode Widths
Nm
2.25
2.2
2.15
2.10
Velocity – matching condition
0
20
40
60
80
100
120
140
160
180
200

Fig. 12


Characteristic Impedance vs. Ground Electrode Widths
Zo (Ohm)
38
36
34
32
0
20
40
60
80
100
120
140
160
180
200
Ground Electrode Widths (um)

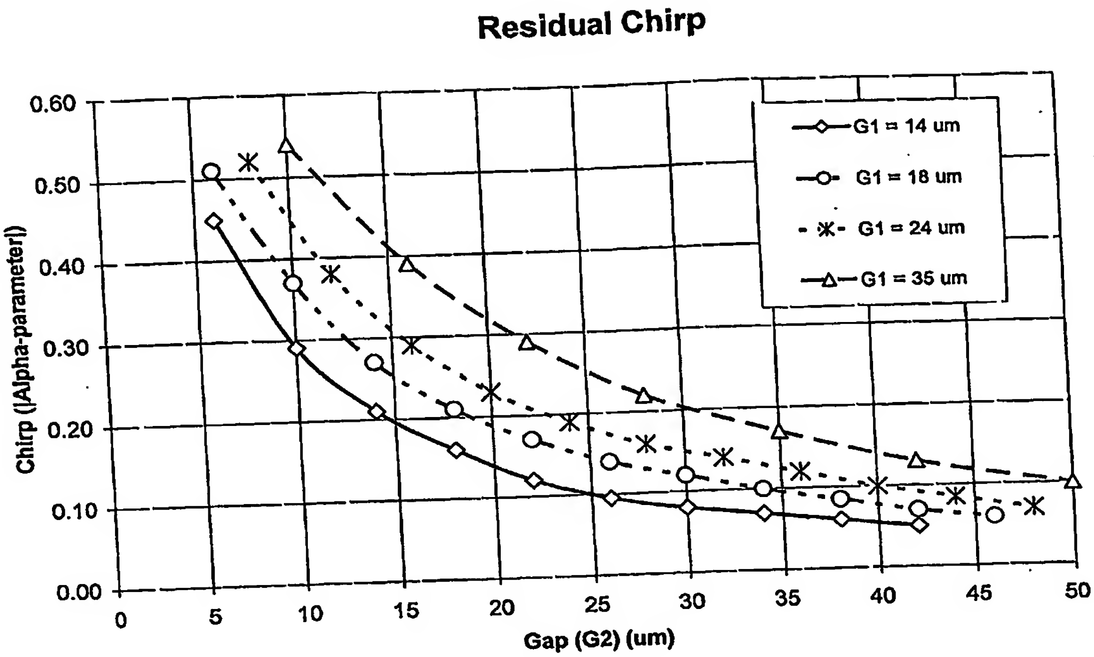

Residual Chirp
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Chirp (|Alpha-parameter|)
0
5
10
15
20
25
30
35
40
45
50
Gap (G2) (um)
G1 = 14 um
G1 = 18 um
G1 = 24 um
G1 = 35 um

Fig. 13

PCT Application
EP0310093